

How Scale Affects Structure in Java Programs

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Abstract

Many internal software metrics and external quality attributes of Java programs correlate strongly with program size. This knowledge has been used pervasively in quantitative studies of software through practices such as normalization on size metrics. This paper reports size-related super- and sublinear effects that have not been known before. Findings obtained on a very large collection of Java programs – 30,911 projects hosted at Google Code as of Summer 2011 – unveils how certain characteristics of programs vary *disproportionately* with program size, sometimes even non-monotonically. Many of the specific parameters of nonlinear relations are reported. This result gives further insights for the differences of “programming in the small” vs. “programming in the large.” The reported findings carry important consequences for OO software metrics, and software research in general: metrics that have been known to correlate with size can now be properly normalized so that all the information that is left in them is size-independent.

Categories and Subject Descriptors Software and its engineering [*Software organization and properties*]: Software system structures

Keywords Object Oriented Programs, Metrics, Linear Regression Models

1. Introduction

Early on in the history of programming, a metaphor was put forward that has seen wide acceptance in the software community: that of programming as LEGO (Figure 1). The metaphor suggests that building large systems is a matter of connecting small standardized bricks together, one at a

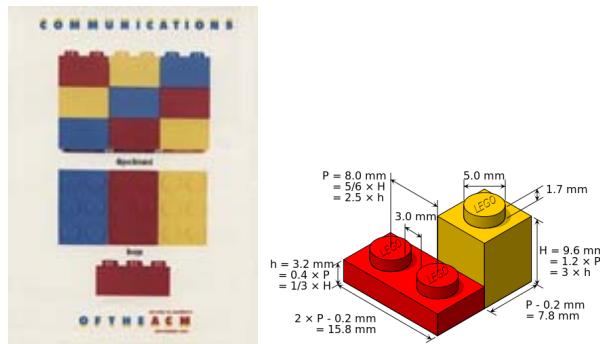


Figure 1. Left: Cover of the CACM, Special issue on Object-Oriented Programming, September 1990 [19]. Right: LEGO bricks showing standard dimensions. (Source: Wikipedia, “Cmglee”.)

time, through their universal interfaces: the small bricks are independent of the scale and purpose of the construction. This metaphor had a tremendous influence in the development of OOP languages. Inspired by the simplicity of the LEGO construction model, these languages placed their focus on mechanisms that would allow to connect small computational units together to create large software systems.

Meanwhile, in 1975 another idea was put forward that has also seen wide acceptance in the software community: that “programming in the large” has different characteristics from “programming in the small.” This idea was first formulated by DeRemer and Kron [8], who argued that “structuring a large collection of modules to form a ”system” is an essentially distinct and different intellectual activity from that of constructing the individual modules.” DeRemer and Kron went on to advocate a “Module Interconnection Language” (MIL) for large systems.

These two popular ideas aren’t mutually exclusive: it is possible to imagine system-wide directives and constraints (i.e. architecture) for large LEGO constructions. But DeRemer and Kron’s essay states a premise that puts some pressure on the LEGO metaphor: “Where an MIL is not available, module interconnectivity information is usually buried partly in the modules, partly in an often amorphous collec-

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tion of linkage-editor instructions, and partly in the informal documentation of the project.” In LEGO terms, this might mean that in order to build a large castle, one might need to plumb stronger connection material into the bricks themselves. In short, the scale of the system would affect the internal structure of the construction.

This paper focuses on the core of these two popular ideas by asking and answering the following question:

Does the scale of the software system affect the internal structure of its modules or are modules scale-invariant?

We want to find out whether there are mathematical principles related to size in large ecosystems of software projects. Besides shedding light on the differences between programming-in-the-small and programming-in-the-large, this question has important implications for research. A common practice for validating ideas in software research is to collect a number of artifacts, either randomly or using some criteria, measure the effects of the ideas using those artifacts, and reach conclusions from the empirical data. Even though size of software artifacts (projects, classes, etc.) has been known to be an issue in quantitative studies of software, software research continues to be fairly oblivious to its effect in these assorted datasets. This is particularly problematic for any studies involving software metrics, including OO metrics. It also affects performance studies that tend to collect data on relatively small programs that aren’t necessarily representative of large programs. Several studies published in the literature may have reached invalid conclusions by ignoring the effect of size or by treating it inappropriately.

The question, as formulated above, is too ambitious to be answered in one single step. This paper takes only the first step. We focus on Object-Oriented software systems, since those are the most influenced by the programming-as-LEGO metaphor; other language families should be studied for broader conclusions. Within OOP, we focus on Java, since it is one of the most popular OOP languages; other OOP ecosystems should be studied for broader conclusions. Finally, we report on a dozen metrics that illustrate the main trends, but many more metrics could be studied.

We deconstruct the general question into five research questions for which specific metrics can be measured:

RQ1 Module size: Are modules of larger systems larger than modules of smaller systems?

RQ2 Module Type: Is there a statistically significant variation in the mix of classes and interfaces for projects of different size scales?

RQ3 Internal Complexity: Are modules of larger systems more, or fewer, complex than modules of smaller systems?

RQ4 Composition via Inheritance: Does the scale of the project affect the use of inheritance?

RQ5 Dependencies: Do larger projects use disproportionately more, or fewer, types from external libraries than smaller projects?

This study puts forward strong evidence that, as programs become larger, the internal structure of the modules and the mixture of composition mechanisms used are affected. As such, the paper makes the following contributions:

1. It unveils strong empirical evidence of the existence of super- and sublinear effects in software that have not been measured before, and it shows concrete parameters of many non-linear relations that underly a large and important ecosystem of Java programs.
2. It proposes more accurate definitions of popular OO metrics that properly normalize for size.
3. By unveiling the characteristics of large projects, it may suggest new ideas for how to tame detrimental non-linear effects, both in terms of programming language design and project management.

2. Motivation and Related Work

It has been almost 25 years since Chidamber and Kemerer published their influential paper on OO metrics at OOPSLA’91 [6]. Since then, OO metrics have been used pervasively in research and development. Here, we review and discuss the main issues with OO metrics, and the research community’s attempts to understand the empirically-based principles of software.

2.1 The Confusing Effect of Size

A large body of literature exists in analyzing how software metrics correlate with software quality. A typical study along those lines involves computing internal software metrics (e.g. coupling of classes) and correlating them with external quality attributes (e.g. post-release bug fixes involving those classes). Many studies of this kind apply simple univariate statistical analysis, and often conclude that there is a correlation.

For quite some time, however, size has been known to be a potential confounding factor in empirical studies of software artifacts. For example, in a study designed to verify whether it is possible to use a multivariate logistic regression model based on OO metrics to predict faults in OO programs, Briand et al. [3] reported strong correlations between class size and several OO software metrics. They then went on to compensate for that correlation by doing partial correlations. In another study of a large C++ system [5], Cartwright et al. also reported such correlations. In 2001, El Emam et al. [9] presented a comprehensive analysis of the effect of class size in several OO metrics, and suggested that this effect might have confounded prior studies.¹ They

¹ We refer readers to [9] for an extensive list of studies that the authors suggest may have reached invalid conclusions by neglecting to compensate for size.

then presented their own study of a large C++ framework which showed that strong correlations resulting from univariate analysis of data were neutralized when multivariate analysis including class size is used. Another more recent study reached the same conclusions when studying the relation between internal software attributes and component utilization [25].

However, Briand et al. and El Emam et al.'s argument has drawn some criticism stemming from the point of view that multivariate analysis of the kind proposed in their papers produces ill-specified, logically inconsistent statistical models [10]. Specifically, the partial correlation of X and Y controlling for a third variable Z , written $r(X, Y|Z)$, is a measure of the relationship between X and Y if statistically we hold Z constant. But trying to predict, for example, the effect on post-release defects X by increasing the coupling value Y while holding the number of lines of code Z constant doesn't make sense, because in the world from where the data comes, increasing coupling usually requires additional lines of code (e.g. field and variable declarations). As Evanco points out [10], this model is inconsistent with the reality of the data. The suggestion following the criticism is that prediction models should use the metric in question Y or the size metric (Z), whichever gives more predictive power, but not both.

Either way, these observations raise doubts about the value of the many software metrics that are correlated with size, as they do not provide any more additional statistical power than what is already provided by their strong correlate – and size is very easy to measure. In summary, size may not be a confounding factor in statistical terminology, but it certainly has been the source of much confusion in software research.

2.2 Non-Normal Data

In their study of slice-based cohesion and coupling metrics over 63 C programs, Meyers and Binkley [20] include correlation coefficients between several coupling and cohesion metrics and Lines of Code (LOC). They show that they are not correlated. We noted that their correlation analysis was made for the entire dataset, which contained components of considerably different sizes; this made the analysis prone to skewness-related errors. In subsequent email exchanges with one of the authors, he kindly shared the data with us; we then verified that, indeed, the distribution of size of the components was not normal but log-normal. Once the transformation to log scale was performed, the data showed moderate-to-strong positive linear correlation between $\log(\text{size})$ and their coupling metric.

This exchange illustrates another source of problems when doing empirical studies of software artifacts, and how size can drastically affect the conclusions. Size is not just a confusing factor; because the projects' size distribution is often skewed, the statistical analysis needs to take non-normal data into account too.

2.3 Software Corpora

In recent years, there has been an increasing number of empirical studies on increasingly larger collections of software projects for purposes of understanding the way that developers use programming languages in real projects. For example, Tempero et al. [26] studied the way Java programs use inheritance in the 100 projects of the Qualitas corpus [27]. The criteria for inclusion of projects in that corpus is relatively strict, requiring, for example, distribution in both source and binary forms.² While their findings fall within the results reported here, the Qualitas corpus contains only 100 projects. The results reported in [26] show that the data does not follow a normal distribution. Another study on the same corpus explored the simulated use of multiple dispatch via cascading instanceof statements [21]. Another study by Gil and Lenz [13] studied the use of overloading in Java programs, also using the Qualitas corpus. Some of the conclusions in these studies (e.g. whether a project is an outlier or not) may be missing the effect of size of the project.

Callau et al. [4] made a statistical analysis of 1,000 Smalltalk projects found in SqueakSource in order to understand the use of certain dynamic features of Smalltalk. They do not report the distribution in terms of project size. The study was designed to gather bulk statistics along an existing taxonomy, so the results are reported as simple counts of feature occurrences among the whole corpus or among a category of projects (e.g. out of 652,990 methods, only 8,349 use dynamic features, and then a breakdown is shown among categories). While the taxonomy is taken into account in the analysis of the data, project size is not. It would be interesting to see whether there is a correlation between the categories and size of the projects.

Collberg et al. [7] randomly collected 1,132 jar files off the Internet and analyzed them (at bytecode level) using a tool developed by the authors. The purpose of that study was to inform Java language designers and implementers about how developers actually use the language. That study reports summary statistics for their entire dataset without taking the distribution of jar size into account. Most distributions shown in the paper aren't normal, so the summary statistics are somewhat misleading. Some of the reported metrics in that study are the same metrics that we use for our study; for example they found on average 9 methods per class, with median 5. The reported values fall within the range of ours, but particularly close to the values for large projects, which leads us to believe that their dataset was biased towards large projects.

In another large study, Grechanik et al. [14] have conducted an empirical assessment of 2,080 Java projects randomly selected from Sourceforge, and discovered several facts about the projects' use of Java. The size of the projects is not reported, and only simple statistics are given. For ex-

² See <https://www.cs.auckland.ac.nz/~ewan/corpus/docs/criteria.html>

ample, the reported mean and median methods per class are 3.5 and 4, respectively. Given that the data does not follow a normal distribution on project size, these values are, again, somewhat misleading and at odds with the findings of Collberg et al. [7]. Like so many large open source code repositories, Sourceforge is severely skewed towards small to medium projects; the reported summary statistics are consistent with our findings for small projects.

In any large corpora of projects, the data rarely follows normal distributions of size, so simple summary statistics such as averages and medians reported in some of these papers provide only weak insights into the principles of those ecosystems, and may hide important phenomena. Also, sample biases may have a large influence on assumptions and conclusions. But what exactly is the effect of size on software artifacts? Can we find general statistical principles that explain the phenomena observed in prior studies?

2.4 Complex Systems

Ours is not the first study to try to unveil internal mathematical structures of software, and the software research community is not the only one looking for mathematical principles in existing software; communities that study complex systems and networks have long found software intriguing. One of the first studies of this kind was by Valverde et al. [29], which analyzed the types and dependencies in the JDK, and noticed the existence of power laws and small world behavior. Soon after, Myers [22] explored what he called “collaboration graphs” (*aka* dependencies) in three C++ and three C applications. Many more studies of this kind followed. For example, [28], [30], [11] and [12] all study the evolution of software networks finding evidence of known mathematical principles that also exist in natural systems, and that might serve as predictive models for software evolution.

Closer to our work, a study presented in 2006 by Baxter et al. [2] also targeted the “Lego Hypothesis,” as coined by the authors. That study, which built on an earlier one by the same group [24], searched for the existence of power laws and other mathematical functions in a collection of 56 Java applications using 17 OO metrics, such as number of methods per type and the number of dependencies per type. For each of those 56 applications, the study revealed whether the 17 metrics’ data points could fit the mathematical functions of interest. The study found that very few projects, and in only very few metrics, had strict power law distributions; most projects, and in most metrics, revealed reasonable fits at 80% confidence interval with several of the functions that they were searching for. Another study by Louridas et al. [18] studied the existence of power laws in a variety of applications written in a variety of languages.

All of these studies largely ignore *application* size, and focus on the modules themselves (i.e. classes, interfaces). In the study by Baxter et al. [2], the results are ordered by application size, and even grouped within size ranges; but no insights are given regarding the effect, if any, that application

size may have on the observations. We believe our study is complementary to all of these prior studies in search for mathematical laws in software applications, because it focuses on the size of the application as a whole, not just on the size of each OO module.

3. Dataset

In this study, we use the Sourcerer 2011 dataset [16], which contains over 150,000+ projects collected from Google Code, SourceForge and Apache as of 2011. The projects have been processed into a relational database of entities and relations, using the Sourcerer Tools publicly available from Github [17]. The database facilitates static analysis for very large collections of source code, as it contains preprocessed static analysis information that can be queried on demand. By issuing specific queries on the database, we extracted the necessary numbers into a Comma Separated Value (CSV) file, which was then used to perform the statistical analysis described in this paper.

The database produced by the Sourcerer tools was, therefore, the basis of our study. We present a small example that illustrates the kinds of entities and relations that are found in the database. Consider the following Java program:

```
package foo;

public class FooNumber {
    private int x;
    FooNumber(int _x) { x = _x; }
    private void print() {
        System.out.println("It is number " + x)
    }
    public static void main(String[] args) {
        new FooNumber(Integer.parseInt(args[0])).print();
    }
}
```

This program results in the entities and relations shown in Tables 1 and 2 (not all entities and relations are shown, for brevity sake). Given this database schema, with these entities and relations tables, we issued several queries in order to extract all the numbers we needed. Here is one example query that extracts the number of methods declared in classes in each of the projects:

```
-- Extract number of class methods per project
SELECT p.project_id, IFNULL(COUNT(DISTINCT m.entity_id),0)
FROM e_methods AS m
INNER JOIN r_contains AS r ON m.entity_id = r.rhs_eid
INNER JOIN e_classes AS c ON c.entity_id = r.lhs_eid
RIGHT JOIN projects AS p ON p.project_id=m.project_id
GROUP BY p.project_id
```

Although the complete dataset contains projects from Google Code, Sourceforge and Apache, for this study, we restricted the analysis to the projects from Google Code only. The main properties of the Google Code dataset are presented in Table 3. Figure 2 shows the size of the projects, from smallest to largest, as well as the histogram of project sizes in the dataset.

Table 1. Entities

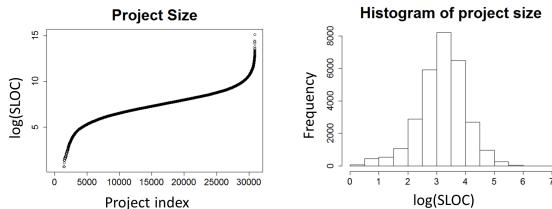
Entity ID	FQN	Type
1	foo	PACKAGE
2	foo.FooNumber	CLASS
3	foo.FooNumber.x	FIELD
4	foo.FooNumber.<init>	CONSTRUCTOR
5	foo.FooNumber.print	METHOD
6	foo.FooNumber.main	METHOD
...

Table 2. Relations

Source	Relation type	Target
1	CONTAINS	2
2	CONTAINS	3
2	CONTAINS	4
2	CONTAINS	5
2	CONTAINS	6
3	HOLDS	<i>Integer_ID</i>
4	WRITES	3
5	READS	3
5	CALLS	<i>println_ID</i>
6	INSTANTIATES	4
6	CALLS	5
...

Table 3. Main metrics of the Google Code dataset.

	Google Code
Projects	30,914
Classes	3,060,853
Interfaces	274,745
Methods	19,358,490
SLOC	221,194,474
Median SLOC	1,570

**Figure 2.** Left: Size of the projects in the Google Code dataset, in Source Lines of Code (SLOC) when projects are ordered by increasing size. Right: Histogram of the size of the projects, in log scale.

This study's granularity is a “project.” For the purposes of this study, a project is the collection of Java source code files that were found in each Google Code Project Hosting’s project pages. For example, the project named 1cproject was hosted at <https://code.google.com/p/1cproject/>, and its source code was available at <https://code.google.com/p/1cproject/source/browse/>. The “project,” in this case, consists of all Java source files found under source control in *trunk*. When the project included jar files, those were considered potential dependencies, not part of the project itself.³

Availability of Data and Tools

The Sourcerer infrastructure and tools are available from Github [17], and have been described before in our prior papers [1, 23]. Besides those two prior publications, a publicly available tutorial explains the processing pipeline of the Sourcerer tools with concrete examples [16]. Additionally, the artifact associated with this paper contains all the Sourcerer tools and a small sample repository of projects, meant to illustrate the processing pipeline by which raw source code is converted into a relational database for static analysis, such as that in this paper. Note that only a small repository is included, because the full repository is 433Gb; its processing into a relational database took approximately 3 weeks of computing on a 24-core, 128 Gb RAM server.

Researchers wanting to reproduce this study, or wanting to study other facets of this data, can start by downloading the artifact associated with this paper, and running the Sourcerer tools installed in it on the included sample repository; then, they can download the full repository from our Web site [16] and run the Sourcerer tools on it.

Having done all this processing ourselves, we are making the processed datasets available to other researchers. The several representations of the Sourcerer 2011 dataset, including the full repository and the database, are publicly available for download from our Web site [16]. Note that this dataset is immutable; it was collected once in 2011, and we do not plan to collect later versions of the projects. The CSV file upon which statistical analysis of this study was done is included in the artifact.

4. Statistical Analysis Methods

This section explains the main statistical methods that were used in this study.

4.1 Linear vs. Log Scales

As mentioned in Section 2, when dealing with large ecosystems of software artifacts, the data is expected to be highly skewed in almost every dimension. That is also the case in the Google Code data. Figure 3 shows a generic illustration of skewness in the data: the left histogram shows that the

³This paragraph is written in the past tense, because Google Code is slated to become unavailable soon.

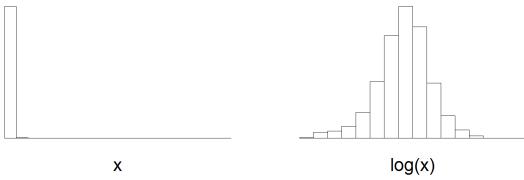


Figure 3. Histograms of log-normal data when plotted in linear scale (left) and *log* scale (right).

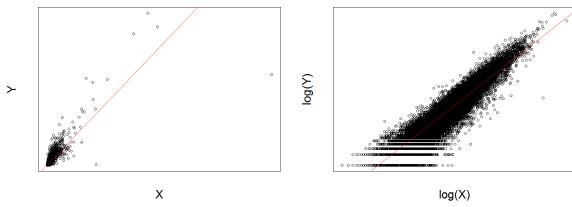


Figure 4. Scatterplots of Y against X when both X and Y are log-normal data. On the left: plot in *linear* scale of X and Y ; on the right: plot in *log* scale of X and Y .

vast majority of data points have small values of X , where X is some measured feature of the dataset; in transforming the data into log scale, however, we can see an almost perfect log-normal distribution (right histogram). When this holds, it would be ill-suited to use normal statistics in linear space, but we can proceed to apply normal statistics in log space. This is a critical step in analyzing these ecosystems.

4.2 Linear Regression Models

The main statistical tool we use in this study is the linear regression model. Linear regression tries to find the best linear model (i.e. a line) that fits the data. Figure 4 illustrates our use of this statistical tool. On the left, we see a scatterplot of some feature X against some other feature Y plotted in linear scale of both X and Y . The plot also shows the best fit line resulting from linear regression of the data. On the right, we see the scatterplot of the same features X and Y but plotted in log scale, along with the best fit line. In both cases, the line is given as $y_values = \alpha + \beta x_values$. However, the plot on the right being in log scale, the straight line represents $\log(y) = \alpha + \beta \log(x)$. Transforming this back to linear space gives the following non-linear (exponential) relation between X and Y :

$$y = e^{\alpha} x^{\beta} \quad (1)$$

When the relation between two features is *non-linear* and, specifically, exponential, some observations are at hand:

- When $\beta = 1$, the relation between X and Y degenerates to linear.
- Any value of $\beta \neq 1$ indicates an exponential relation between the two features. Small variations in β represent large variations of Y against X in linear space.

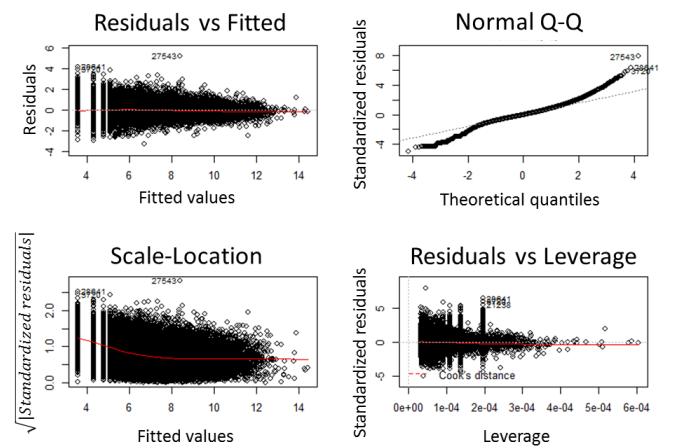


Figure 5. Residuals plots. Top-left: Residuals vs Fitted. Top-right: Normal QQ. Bottom-left: Scale-location (aka spread). Bottom-right: Residuals vs Leverage.

- $\beta > 1$ indicates a superlinear relation, i.e. Y grows exponentially faster as X grows.
- $\beta < 1$ indicates a sublinear relation, i.e. Y grows exponentially slower as X grows.

4.3 Goodness of Fit

One critical part of linear regression is the goodness of fit, that is, how well the line fits the data. R^2 , pronounced R-squared, is a statistic that measures how successful the fit is in explaining the variation of the data.⁴ For example, $R^2 = 0.92$ means that the fit explains 92% of the total variation in the data. A value of 1 would be the perfect fit.

However, due to how it is calculated, there are several limitations for what R^2 can explain. Depending on the characteristics of the data, R^2 can have a low prediction value. In order to verify this, it is important to analyse the *residuals* of the linear regression models. Figure 5 illustrates the kinds of residuals plots that we analyze to check whether the linear models are appropriate or not. The *Residuals vs Fitted* plot (top-left) is the most important one. A good fit should result in this plot showing randomly distributed data around the horizontal line at the origin, meaning that what's left from the fit is unbiased noise – this particular plot shows that. When this doesn't happen, then the linear model may not be appropriate to explain the data, even if R^2 is high. The *Normal QQ* plot (top-right) illustrates assumptions about normality of the residuals in the model. When the dots all fall in the straight diagonal, then the residuals fit exactly a normal distribution, which is the ideal case. This particular plot shows a symmetrical light-tailed normal distribution of the residuals, which is acceptable. In general, some deviation

⁴ $R^2 = 1 - \frac{SSE}{SST}$, where SSE is the residual sum of squares and SST is the total sum of squares.

from the norm is to be expected, particularly near the ends. The *Scale-Location* plot, also known as *spread*, illustrates the variance of the Y variable along the X variable. A flat line means that the variance is constant along X, which is the ideal case for linear regression. This particular plot shows that there is more variance for lower values of X, and then the variance evens out. This kind of small deviation from the ideal is acceptable. Finally, *Residuals vs Leverage* illustrates the *leverage* (influence) that the data points had on the fitness process. This plot serves to identify potential outliers that may have had undue influence in the model. We want the points to fall as close as possible to the horizontal line at origin, and not to fall outside Cook's distance. That is the case with this particular plot.

4.4 Binned Analysis

When the residuals of the linear models show potential problems with the model, that means that the simple linear regression models are missing important characteristics of the data. In those cases, we try to perform binned analysis instead of analysis on the whole data. This analysis is meaningful when the data in the bins shows normal distributions. When that is the case, we compare the differences of means among the bins using Welch two sample t-test on a 95% confidence interval in order to extract more meaningful insights.

5. Findings

This section presents the main findings of our study. It starts with observations regarding the size of the modules, then their complexity, the use of inheritance, and finally the kinds of dependencies the modules have. It should be noted that all linear models and correlations presented here are statistically significant, with p-values << 0.0001.

5.1 Module Size

RQ1: *Are modules of larger systems larger, or smaller, than modules of smaller systems, or are there no statistically significant differences?*

In Java, the modular, replaceable units are classes and interfaces, so we use the word *module* to mean either a class or an interface. The bivariate analyses used to study the above question are: SLOC vs. Modules, Methods vs. Classes and Constructors vs. Classes. We know from several previous studies that these pairs of metrics are strongly positively correlated. But what exactly is the nature of these relations?

Figure 6 sheds some light into this question. On the top, the size of each project in SLOC is plotted against its number of classes and interfaces. As expected there is a very strong linear correlation ($r = 0.93$). Moreover, with 87% linear fitness (in log space), it appears that as the number of modules grows, the lines of source code also grows but at exponentially higher pace. Specifically, using equation 1,

$$SLOC = e^{3.5549} \text{Modules}^{1.0939}$$

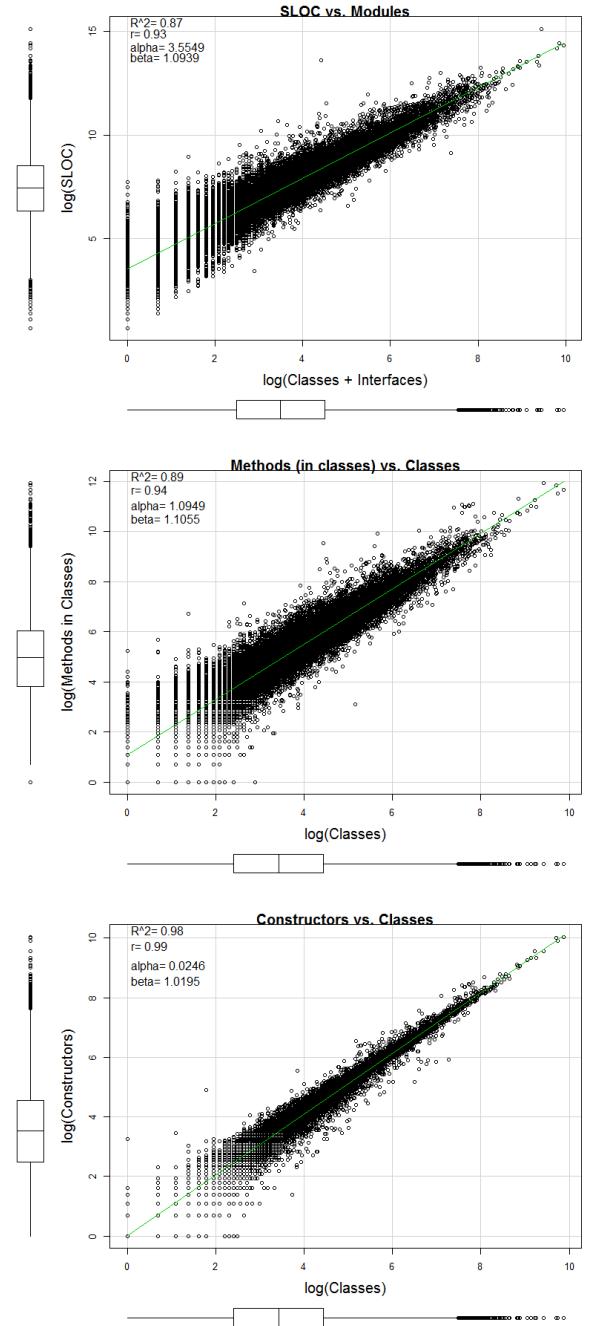


Figure 6. Top: SLOC vs. number of modules. Middle: Number of methods vs. number of classes. Bottom: Number of constructors vs. number of classes.

Table 4. Analysis of project size.

Analysis	α	β	r	R^2	Space
SLOC vs. Modules	3.5549	1.0939	0.93	0.87	log-log
Meths. vs. Classes	1.0949	1.1055	0.94	0.89	log-log
Constrs. vs. Classes	0.0246	1.0195	0.99	0.98	log-log

For example, a project with 10 modules is predicted to have close to 434 SLOC; a project with 100 modules is predicted to have not just 4,340 but close to 5,391 SLOC, so considerably more than 10 times what's expected of a project with 10 modules; a project with 1,000 modules is predicted to have close to 66,923 SLOC, again considerably more than 10 times what's expected of a project with 100 modules; etc. The growth of SLOC is exponential with number of modules, and even though the exponent (1.0939) is close to 1, the small 0.0939 difference results in large differences in the linear space.

Where do all these extra lines of code go? The middle plot in Figure 6 explains it. The plot shows the number of methods declared in classes vs. the number of classes. Again, as expected, there is a strong positive linear correlation ($r = 0.94$). Moreover, with 89% linear fitness, it appears that as the number of classes grows, the number of methods grows exponentially. Specifically,

$$Methods = e^{1.0949} Classes^{1.1055}$$

For example, a project with 10 classes is predicted to have close to 38 methods; a project with 100 classes is predicted to have not just 380 but close to 486 methods; a project with 1,000 classes is predicted to have close to 6,195 methods; etc. Again, the growth of the number of methods is exponential, not linear.

A similar exponential growth can be observed for constructors vs. classes (Figure 6, bottom). The relation in that case is $Constructors = e^{0.0246} Classes^{1.0195}$. In this case, β is very close to 1, so this is almost a linear function.

In short: projects with **more modules** have disproportionately more lines of code than projects with less modules, which means that they have **larger modules**. Moreover, the extra lines of code seem to be grouped in disproportionately **more methods** and, to a lesser degree, constructors, **per class**.

Table 4 summarizes the statistical principles inferred from the data related to the effect of size. α and β are the coefficients for equation 1; r is the Pearson correlation coefficient of the data in log scale; R^2 is the fitness of the line in log space. The residuals of the linear model can be found in Figures 11, 12 and 13. All of them show good strength of the model.

These observations explain apparent inconsistencies in the literature over the past few years. As described in Section 2, different studies of Java corpora have reported different average methods per class. This could potentially be explained by our findings: a corpus that is dominated by

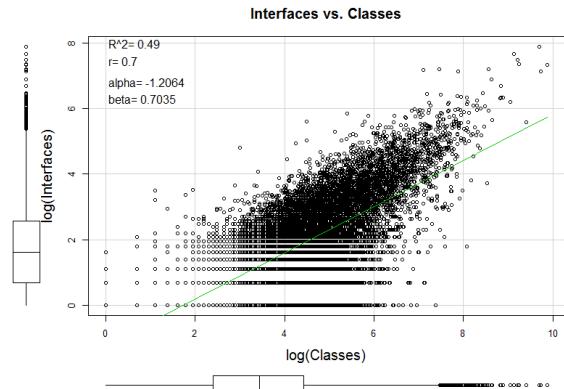


Figure 7. Interfaces vs. classes in log scale.

smaller projects will have lower average methods per class than a corpus dominated by larger projects.

5.2 Module Types

RQ2: *Is there a statistically significant variation in the mix of classes and interfaces for projects of different scales?*

The answer to the question involves dealing with data that shows high variance. We started by regressing the number of interfaces against the number of classes in each project, similarly to what we did for the previous question. Figure 7 shows the non-linear model:

$$Interfaces = e^{-1.2064} Classes^{0.7035}$$

$R^2 = 0.49$ is not too good of a fit. Visual inspection of the plot and the fitted straight line exposes weaknesses of this simple linear model, particularly at the edges of the data: for projects with very small and very large classes, the model underestimates the number of interfaces. Clearly, the relation between the number of classes and the number of interfaces in this ecosystem is not properly explained by a simple exponential function.

The observations from visual inspection are confirmed in the plots of the residuals in Figure 14 (Appendix B). The *Residuals vs Fitted* plot, in particular shows a bend in the residual data, rather than a straight line. This is indicative that the linear model is missing a non-linear component. The shape of the bend suggests a parabola, so we add an additional transformation of the X variable, specifically $\log(X)^2$, and perform a linear regression on that transformed space ($\log(y) \sim \log(x)^2$). This additional transformation introduces non-monotonicity (see Appendix Figure 37). Transforming this back to linear space, we are establishing the relation:

$$y = e^\alpha x^\beta \log(x) \quad (2)$$

The plot is shown in Figure 8 and the residuals plots are in Appendix B, Figure 15. As can be seen, this is a better fit, with $R^2 = 0.52$. The bias in the fit that transpired with the bend in the residuals plot is now practically eliminated. Given the parameters, this model predicts

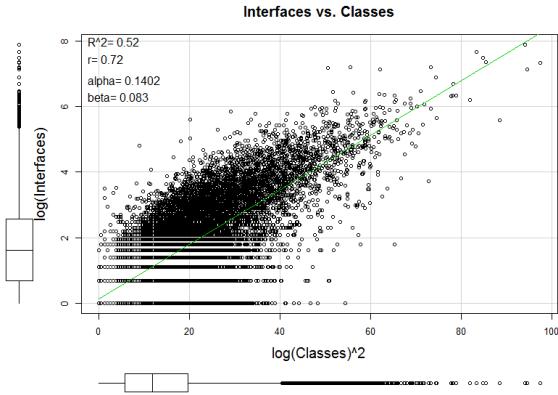


Figure 8. Interfaces vs. classes in \log^2 scale.

Table 5. Bins for analysis of *Interfaces/Classes*. Mean and SD values are in log scale.

Bin	# Classes	Projects	Mean (linear%)	SD
V. Large	> 5,000	17	-2.47 (8.5)	0.87
Large	1,000 – 5,000	419	-2.83 (5.9)	1.00
Medium	100 – 1,000	5,762	-2.77 (6.3)	1.05
Small	20 – 100	11,715	-2.49 (8.3)	0.92
V. Small	< 20	11,557	-1.68 (18.6)	0.78

$$\text{Interfaces} = e^{0.14} \text{Classes}^{0.083 \log(\text{Classes})}$$

Note that due to the non-monotonicity illustrated in Figure 37, this model establishes a variable ratio between classes and interfaces depending on project size. Specifically, smaller projects have a much higher ratio *Interfaces/Classes*.

For example, for a project with 10 classes, the model predicts 1.79 interfaces ($\sim 18\%$ ratio); 50 classes $\succ 4.1$ interfaces ($\sim 8.2\%$); 100 classes $\succ 6.69$ interfaces ($\sim 7\%$); 1000 classes $\succ 60.4$ interfaces ($\sim 6\%$). According to the model, the ratio proceeds to increase again for very large projects. For example 10,000 classes $\succ 1,314$ interfaces ($\sim 13\%$). Our dataset includes only 6 projects that contain over 10,000 classes each, so the model may not be precise for this end of the size spectrum.

Another way of analyzing this data is to make a binned analysis. For that, we divide the data into 5 bins on the number of classes: very large, large, medium, small and very small. We then compute the ratio *Interfaces/Classes* for all the projects, and compute the means of the ratios in each bin. The results are shown in Table 5.

Finally, we perform a Welch two sample t-test on the differences of means to check whether the differences exist and are statistically significant. The tests show statistical significance ($p < 0.0001$) on the mean differences between medium and small, and between small and very small. The other differences are not statistically significant at 95% confidence level.

Table 6. Analysis of code complexity

Analysis	α	β	r	R^2	Space
Calls vs. Methods	1.64	1.00	0.94	0.89	log-log
Inst.of vs. Methods	-2.77	0.84	0.70	0.49	log-log
	-0.41	0.01	0.72	0.52	log-log ²
Casts. vs. Methods	-1.81	1.00	0.83	0.68	log-log
	-0.49	0.36	0.84	0.70	log-log ^{1,4}

The numerical values of the binned analysis are consistent with those from the linear regression model that places the number of interfaces as a continuous function of the number of classes as by equation 2. This adds strength to the result.

One possible explanation for why smaller projects have disproportionately more interfaces is that they have an investment in modeling entities with interfaces without having enough implementations of those entities to pay off the investment. In medium-to-large projects, that investment pays off, as more classes provide alternative implementations of the interfaces. The higher ratio in very large projects is not statistically significant, so no conclusions should be made on whether that holds in general or only in this particular set of 17 very large projects.

5.3 Internal Complexity

RQ3: *Do larger projects have more method calls or use more unsafe operations than smaller projects, or are there no statistical significant differences?*

A recent study by Landman et al. [15] showed that there seems to be no correlation between the size of Java projects (measured in SLOC) and the cyclomatic complexity of their methods. We go one step further to investigate other potential sources of complexity in code: the number of outgoing methods calls, the number of instanceof statements and the number of unsafe type casts in each project.

Like for module types, some of the data here also has a considerable variation. Table 6 summarizes the results. We found no evidence that larger projects use more unsafe features of Java than smaller projects, and we found some weak evidence that the contrary may happen.

5.3.1 Method Calls vs. Methods declared in classes

In the case of method calls, there is a fairly strong fit of the linear model ($R^2 = 0.89$), and the residuals plots show no warning signs (Appendix B Figure16). The exponent $\beta = 0.9971$, however, is very close to 1, which means that the relation is essentially linear at a rate of $e^{1.64} = 5.1$ calls per method. For example, according to the model, a project with 50 methods has 255 method calls; a project with 500 methods has 2,531 method calls; a project with 5,000 methods has 25,144 method calls.

5.3.2 Instanceof statements vs. Methods declared in classes

In the case of `instanceof`, the linear model in log-log space is not that good ($R^2 = 0.49$), and the residuals plots show some warning signs (Appendix B Figure 17). Similarly to what was done for the previous analysis, we transformed the X axis (methods) with an additional square function, and the fit improved to $R^2 = 0.52$ (residuals in Appendix B Figure 18). This yields the relation

$$\text{Instanceof} = e^{-0.14} \text{Methods}^{0.0702 \log(\text{Methods})}$$

Again, this function is not monotonic, and therefore results in a non-monotonic average number of `instanceof` statements per method, depending on the total number of methods of the projects: the ratio starts high for projects with just a few methods (e.g. 0.21 for projects with 5 methods) and decreases sharply for projects with very small number of methods (< 20); it then continues to decrease but more gently, reaching a minimum of 0.025 `instanceof` statements per method for projects with around 1,000 methods (i.e. almost 10 times less than for projects with 5 methods); from then on, it increases again, but slowly. Its predicted value is 0.06 `instanceof` statements per method for projects with 50,000 methods (of which there are 17 in the dataset).

5.3.3 Type casts vs. Methods declared in classes

In the case of casts, the linear log-log model is also not that good ($R^2 = 0.68$, see also Appendix B Figure 19). We then tried a few transformations, and found $\log^{1.4}$ to produce very good residuals plots (Appendix B Figure 20) and a better $R^2 = 0.70$. This function has a similar behavior as the one explained for `instanceof` in terms of monotonicity, but the minimum (0.13 casts per method) happens a bit earlier, at around 500 methods. This value of casts per method is roughly 10 times less than the value for projects with 5 methods.

5.3.4 Discussion

Combined, and along with the study by Landman et al., these results show that there is no evidence to support the hypothesis that larger projects have more complex code. On the contrary, there seems to be a trend for smaller projects to include proportionally more unsafe statements of Java.

The linear model method calls vs. methods (Section 5.3.1) is a fairly strong fit that shows that the number of method calls per declared method is roughly constant and independent of the size of the projects (measured in number of methods). The other two models (Sectons 5.3.1 and 5.3.2) have a less strong fit. That simply means that their precision as predictors is not too good, but the trend showing proportionally more unsafe features of Java in small projects (Section 5.3.3) is interesting and statistically significant. We conjecture that this may happen because developers of non-trivial projects adhere to a stricter discipline of avoiding these features.

Table 7. Analysis of inheritance

Analysis	α	β	r	R^2	Space
DUI vs. Classes	-1.0505	1.0159	0.92	0.85	log-log
	-0.5364	0.6626	0.93	0.86	log-log ^{1,2}
IF vs. Classes	-1.9908	0.8037	0.78	0.61	log-log
	-0.3414	0.0903	0.80	0.64	log-log ²

5.4 Class Composition via Inheritance

RQ4: *Does the scale of the project affect the use of inheritance?*

The two linear models used to answer the above question are classes defined using inheritance (DUI) vs. total classes, and classes that are inherited from within the project (IF) vs. total classes of each project. The results are shown in Table 7 (plots in Appendix 21, 22 23 and 24).

As in previous analysis, the residuals plots of the initial linear regression models showed some warning signs that the models might not be the best (Appendix B Figures 22 and 24). As such, we compensated for the bend in the residual data by adding an additional non-linear components to the X axis (classes).

5.4.1 Classes Defined Using Inheritance (DUI)

In the case of DUI classes vs. classes, the better model is $DUI = e^{-0.5364 + 0.6626 \log(\text{Classes})^{1,2}}$

Also here, the curve of the ratio starts high, decreases sharply, then decreases slowly up to a minimum, then increases again. In the case of these parameters, the minimum is around 10 classes, with 35% of them DUI. According to this model, projects with 2 classes have on average 0.9 of them defined using inheritance (45%); 10 classes $\succ 3.5$ (35%); 100 classes $\succ 37$ (37%); 1,000 classes $\succ 493$ (49%); 5,000 classes $\succ 3,379$ (68%); etc.

A project with 100 classes, 65% of them DUI, is far from the norm, but if the number of classes is close to 5,000, then that percentage of DUI is close to the norm.

5.4.2 Classes Inherited From (IF)

In the case of IF classes, the better model is $IF = e^{-0.3414} \text{Classes}^{0.0903}$

In the case of these parameters, the minimum is around 100 classes, with 5% of them DUI. According to this model, projects with 10 classes have on average 1.1 inherited from (11%); 100 classes $\succ 4.8$ (5%); 1,000 classes $\succ 52.8$ (5%); 5,000 classes $\succ 3,379$ (10%); etc.

5.5 Dependencies

RQ5: *Do larger projects use disproportionately more, or fewer, modules than smaller projects? How does project effient coupling vary with size? Are there statistically significant differences in how types from JDK/internal/external libraries are used in projects of varying sizes?*

To answer these questions, we first look at the growth of the number of distinct types used by projects vs. the growth

Table 8. Analysis of used modules

Analysis	α	β	r	R^2	Space
Used vs. Declared	2.006	0.7357	0.93	0.87	log-log ^{1.2}
	2.335	0.4863	0.93	0.87	log-log ^{1.2}

of the number of modules⁵ declared in the projects. In counting the number of modules used, we count the number of *distinct* modules, so modules used multiple times in a project are counted only once. We then look deeper into the origins of the used modules.

5.5.1 Used Modules vs. Declared Modules

Projects use a variety of modules, some of them declared internally, others provided by the JDK and others provided by external libraries. Again, we know that the number of modules used in a project is highly correlated with the size of the project. We are interested in studying the underlying trend function, and whether it is linear or super-/sub-linear. Project size here is measured by the number of declared modules in it.

In analyzing the initial linear regression model in log-log space, it was visible that it suffered from a small bend in the residuals (see Appendix B Figure 25.) We then compensated for it by applying a polynomial of size 1.2, which eliminated the bend, producing a better model. Table 8 summarizes the parameters.

The better model establishes the following relation between the number of used modules and the number of declared modules in a project:

$$Used = e^{2.3353 + 0.4863 \log(Modules)^{1.2}}$$

These parameters define a sub-linear relation between the number of used modules and the number of declared modules in a project, meaning that the number of distinct used modules increase disproportionately less than the number of declared modules in projects. According to this model, projects with 10 declared modules use on average 39 modules; 100 declared $\succ 216$ used; 1,000 declared $\succ 1,450$ used; etc. The number of used modules grows slower than the number of declared modules.

This result is intriguing, as it was unclear what to expect. The result makes sense when the addition of a dependency (external or internal) is correlated with the addition of multiple modules internal to the project; the causal relation is unclear, and there may be unknown confounding factors behind this correlation.

Theoretically, according to this model, there is a scale point at which the number of used modules is less than the number of declared modules, which means that some declared modules would not be used, just declared. That point is around 50,000 declared modules. Our dataset does not contain any project that large, but we found 753 projects where the number of declared modules is larger than the

⁵ Again, we use the term modules = types = classes + interfaces.

Table 9. Analysis of efferent coupling of projects

Analysis	α	β	r	R^2	Space
Coupling vs. SLOC	0.1176	0.5641	0.91	0.82	log-log

Table 10. Analysis of origin of dependencies (I)

Analysis	α	β	r	R^2	Space
Inter. vs. Modules	-0.5040	1.0037	0.96	0.92	log-log
JDK vs. Modules	1.7405	0.5306	0.81	0.66	log-log
Exter. vs. Modules	0.7168	0.7489	0.80	0.65	log-log

number of used modules, so this situation is not rare. An analysis of this set of projects shows that they are statistically larger than the average of the whole dataset, and that it contains a disproportionate number of very large projects – 17 out of the 59 projects with more than 3,000 declared modules are in this subset of projects that have higher number of declared modules than used modules. It is possible that these cases correspond to utility frameworks.

However, the opposite result, if it had been observed, could also be explained. That is, one could imagine that the number of used modules would grow faster than the number of declared modules. In this case, the addition of a dependency (external or internal) would not be correlated with additional internal modules, and, instead, it would simply correlate with the addition of methods in existing modules that use that new entity. That is not the case in this ecosystem: more methods seem to exist for defining additional functionality with existing dependencies than new methods are added for using additional dependencies. (plots omitted for space reasons)

5.5.2 Efferent Coupling vs. SLOC

The efferent coupling of an entire project is given by the number of external modules (classes+interfaces) that the project uses. Here we study its exact relation with project size given in SLOC. This analysis targets the well-known correlation between efferent coupling metrics and size of artifacts, in general. Table 9 summarizes the parameters. (Plots are in Appendix B Figure 27)

According to this model, the relation is sublinear, i.e. efferent coupling grows disproportionately slower than SLOC. Also, here, “normality” changes with scale, it’s not a simple constant ratio.

5.5.3 Provenance of Used Modules

In order to find out whether there are differences in the origin of dependencies among projects of different sizes, we then looked at the provenance of all classes and interfaces (i.e. modules) that are used in each project, and regressed them against size of the project, given by number of declared modules. Table 10 summarizes the parameters. (All residuals plots can be found in Appendix B, Figures 28, 29 and 30)

Table 11. Analysis of origin of dependencies (II)

Analysis	α	β	r	R^2	Space
Inter. vs. Total	-2.882	1.282	0.93	0.87	log-log
	-2.821	1.275	0.93	NA	log-log (RLM)
JDK vs. Total	0.162	0.750	0.90	0.82	log-log
	0.153	0.756	0.90	NA	log-log (RLM)
Exter. vs. Total	-1.585	1.072	0.89	0.79	log-log
	-1.454	1.059	0.89	NA	log-log (RLM)

Indeed, these parameters show that there are differences. As β indicates, larger projects use disproportionately less modules from external sources ($\beta = 0.7489$) and even less from the JDK ($\beta = 0.5306$) than smaller projects. They use slightly disproportionately more internally-defined modules ($\beta = 1.0037$) than smaller projects.

These numbers are highly driven by the previous result – in general, the number of used modules grows slower than the number of declared modules. That blurs the true ratios of the origin of dependencies as projects grow, so let us analyze the data in a different way. We can take module use as the independent variable and module origin as the dependent variable. This helps us quantify the mix of dependency provenance as a function of project size given by the number of total used modules (i.e. a slightly different size metric that is highly correlated with the number of declared modules). The results are shown in Table 11.

An inspection of the residuals plots (Appendix B Figures 31, 32 and 33) suggested that the simple linear model may suffer from the effect of outliers, particularly on the use of JDK entities. As such we performed a *robust* linear regression model (RLM), which excludes outliers.⁶ The new residuals plots (Appendix B Figures 34, 35 and 36) still suffer from some left-skewness, but the *Residuals vs. Fitted* plot shows an improvement. Even with RLM, the model may not be strong for the edges of the data, i.e. for extremely small and extremely large projects.

The results indicate that, as the number of total used modules grows, projects use disproportionately much less of the JDK ($\beta = 0.7559$) and much more internal ($\beta = 1.2822$) modules. The growth in external dependencies is also disproportionately larger, but less so than the use of internal modules ($\beta = 1.0589$).

In retrospect, this result makes sense: the reason why projects are larger is that they define more classes and interfaces; those are likely to be used internally. For large projects, and given that the amount of types in the JDK is fixed, the relative importance of the types from the JDK decreases and the importance of internal types increases.

But this result exposes an interesting characteristic of programming-in-the-large: larger projects use much more of their internal, and potentially less stable, components. Smaller projects leverage the JDK.

⁶Robust linear regression does not report R^2 .

Table 12. Alternative models for Methods vs. Classes

Model	Subset	#Projects	α	β	R^2
1	Baseline	30,914	1.095	1.106	0.89
2	[10–3,000]	22,860	1.283	1.061	0.84
3	[20–3,000]	18,239	1.335	1.051	0.82
4	[30–3,000]	15,030	1.347	1.049	0.81
5	[50–1,000]	10,576	1.350	1.047	0.73
6	[100–500]	5,167	1.232	1.068	0.52
7	[10–100]	16,712	1.222	1.081	0.63
8	[1,000–3,000]	386	0.168	1.218	0.36

6. Sampling Biases

The linear regression analysis in the previous section was performed over the entire dataset without excluding any of the projects. The dataset is heavily right-tailed, with a bias towards small projects, and with only a few very large projects. Since linear regression learns the parameters α and β from the data, the data that we use influences the exact values of those parameters. As such, it could very well be that the non-linear effects that have been reported in the previous section, given by $\beta \neq 1$, could be an artifact of the many small projects and the very few very large projects in the dataset forcing that non-linear behavior in order for the models to fit the data. If that were to happen, there might be a simpler linear model with $\beta = 1$ that could perfectly explain the data “in the middle” containing only projects above and below certain size thresholds. In other words, we could give up explaining what happens for the many very small projects, because the variance in them is very large, and for very large projects, because there aren’t that many, and focus on finding simple models for projects in between.

We investigated this possibility by constructing alternative models where the parameters are learned from various subsets that exclude very small and very large projects. We report the result on only one of the many bivariate analysis of the previous section, specifically Methods vs. Classes, which had $\beta = 1.1055$ (Section 5.1). Table 12 summarizes the results. The column Subset in that table denotes the conditions for project inclusion in the set as a range on the number of classes in the project. The first row is the baseline model given in the previous section. All of these models result in good residuals without any warning signs.

As shown in the table, all of the alternative models are still non-linear, with $\beta \neq 1$, but, with the exception of model 8, the value is lower than the baseline model. Model 5, which excludes almost 2/3 of the dataset and includes the projects in the middle of the dataset, has the lowest β . But even in that subset, the non-linear relation between classes and methods can be observed. According to the parameters of model 5, a project with 50 classes is predicted to have 232 methods, and a project with 500 classes is predicted to have, not 2,320, but 2,583 methods. Any concerns that the non-linear relation between methods and classes was an artifact of sampling bias are put to rest with the results shown in Table 12.

Table 13. Accuracy of the models, measured in NRMSE

Model	V.Small (5,472 projects)	V.Large (50 projects)	All (30,914 projects)
1	0.13467	0.1500	0.05110
2	0.13109	0.1229	0.05155
3	0.13083	0.1210	0.05181
4	0.13081	0.1208	0.05188
5	0.13078	0.1204	0.05189
6	0.13171	0.1230	0.05136
7	0.13184	0.1354	0.05135
8	0.21137	0.1530	0.05700

Given that there can be an unlimited number of models inferred from any arbitrary subset of the original dataset, the question arises of which model to use.

If the goal is to make predictions based on the models, the accuracy of each model can be tested on test datasets that aren't part of the data from which the models are learned. We exemplify such prediction goals by measuring the Normalized Root Mean Square Error (NRMSE) of each model on the two extremes of the whole dataset that have been eliminated from the learning part: the very small projects ($\#Classes < 10$) and the very large projects ($\#Classes > 3,000$); note in Table 12 that those projects are not part of any subset. NRMSE is given by

$$RMSE = \sqrt{\frac{\sum_{t=1}^n (\hat{y}_t - y_t)^2}{n}} \quad (3)$$

$$NRMSE = \frac{RMSE}{y_{max} - y_{min}}$$

The summary of this accuracy analysis can be seen in Table 13. For comparison, we also show the NRMSE of each model on the entire dataset. Numbers in bold represent the models that performed the best.

As expected, the model that performs the best for the entire dataset is model 1, whose parameters were inferred from that same data. This case doesn't serve to validate the model, it just confirms what was expected. Excluding that baseline, the model that performs the second best on the entire dataset is model 7, which contains many small projects. The real validation comes only on the performance of the models on the two test sets containing very small and very large projects, which weren't contained in the learning data. In both cases, the model that makes the best predictions is model 5, whose parameters are inferred from a large portion of small/medium/large size projects.

Given these results, model 5, which learns the parameters ignoring the edges of the data, should be used instead of the baseline model 1. Similar accuracy analysis should be done for all the other bivariate analysis. It is likely that the best models are always the ones that learn the parameters ignoring the projects at the edges, where there is either more

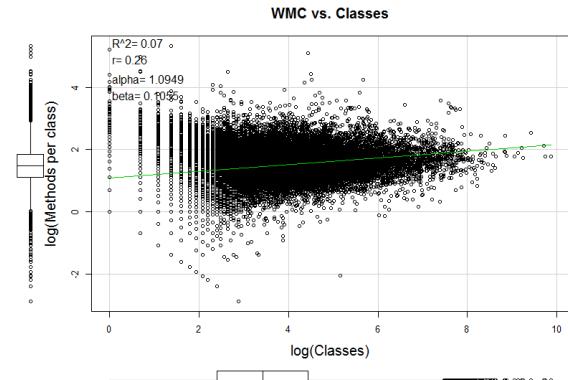


Figure 9. Correlation: how WMC grows with the number of classes.

variance or uncertainty. Nevertheless, the most important take away from this section is that **the non-linearities exist in the data, independent of which subsets we choose**.

7. Implications for Software Metrics

Our study was centered around a very simple question: *does the scale of the software system affect the internal structure of its modules or are modules scale-invariant?*

For the Java ecosystem, the answer is: yes, the scale of the system affects several aspects of the internal structure of its modules, and of the way the modules are put together. Among those, the number of methods per class, the number of LOCs per module, the use of inheritance and mix of dependencies stand out. Going back to the LEGO metaphor, it is as if large Java projects have injected stronger coupling material and more hooks into the [larger] software bricks. These findings have profound implications for software research, especially quantitative studies of software artifacts. We discuss them here.

As mentioned in Section 2.1, size has been the source of much confusion in software studies. As noted several times in the literature, many software metrics – for example, Weighted Methods per Class (WMC) and (efferent and afferent) Coupling, just to mention two – are correlated with size, so their statistical power is very weak when size metrics are available. We explain how to properly normalize for size with one example metric: WMC.

Figure 9 shows the regression of WMC vs. Classes in our dataset, a confirmation of what we already know about the existence of these correlations. In our data, the Person correlation (in log space) is $r = 0.3$, so moderately strong.

7.1 Linear or Log?

A first approach to normalizing the number of methods controlling for size of the project is to make a simple average $WMC = Methods/Classes$. This is, in fact, how this metric is defined in the literature [6], assuming uniform complexity of 1 (an assumption made in several prior

studies). This gives us a number that, in principle, can be used to compare projects independent of their size. If we have two projects, one with $WMC = 3$ and the other with $WMC = 8$, that tells us that these two projects are considerably different without needing to know any size metric.

In software ecosystems, a mean of WMC can be calculated for entire collections of projects by computing the WMC of all the projects in collection, and then computing the mean of those values. In our dataset $mean(WMC) = 5.15$, which might lead us to conclude that in this very large Java ecosystem, the average WMC is 5.15.

This value, however, is very misleading, because the distribution of WMC in the dataset is not normal, but log-normal. Figure 38 in Appendix shows the WMC distribution in linear and log scales.

Given this knowledge, a second approach to normalizing for size is to find the mean and SD of WMC in log scale. In our dataset that is $mean(WMC)_{log} = 1.455$ and $SD(WMC)_{log} = 0.63$. This translates to linear space as 4.28, with 68% of values falling within the interval [2.28 – 8.00], skewed towards the lower end of the interval.

The first thing to notice is that these two numbers, $mean(WMC)$ and $mean(WMC)_{log}$ are different, the former being larger than the latter. That happens because the data is highly right-skewed, i.e. there are many more smaller values than larger ones. Therefore the simple mean in linear scale does not capture an important aspect of the data, its skewness; the mean and SD in log scale do. Another way of looking at this is that when drawing a data point randomly out of this dataset, the odds are higher around 4.28 than around 5.15.

Even though this is basic statistics, many papers continue to report summary statistics in linear scale when the data is not normally distributed in that scale. In general, we must inspect what kind of distribution our data has and report summary statistics accordingly, or the reports will be misleading.

7.2 Non-Linearity

The above analysis is still missing something important about the data, namely the findings unveiled by this paper that the number of methods in a project grows *disproportionately* faster with the number of classes. Therefore *normality* takes a different value depending on the scale of the project. We might conclude that a project with $WMC = 7.9$ ($WMC_{log} = 2.067$), which is on the edge of the SD interval, might need special attention, and that a project with $WMC = 4.3$ would be perfectly “normal.” That may or may not be the case, depending on the size of that project. In Section 5.1 we found a strong non-linear model given by:

$$Methods = e^{\alpha} Classes^{\beta}$$

This equation gives us the *norm* of what to expect of WMC in projects of varying sizes in this dataset. For a project with 10,000 classes, the expectation of the model is that it will have 70,000+ methods, not 42,800 as a simple linear model would predict (i.e. $4.28 * 10,000$); so $WMC =$

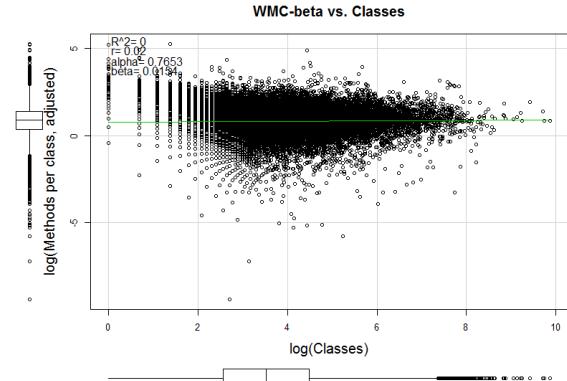


Figure 10. Normalization: how WMC_{β} grows with the number of classes.

7.9 is what we would expect for a project of this size. A project with 10,000 classes that shows $WMC = 4.3$ would be an oddity in this ecosystem. If, however, the project has only 25 classes, then $WMC = 4.3$ would be expected, but $WMC = 7.9$ would be surprising, in the sense that it is a large deviation from what is expected of projects of that size.

Therefore, the proper normalization for size must take this non-linear relation into account, producing an adjusted ratio that is *truly* independent of the number of classes:

$$WMC_{\beta} = \frac{Methods}{Classes^{\beta}} \quad (4)$$

Figure 10 shows how WMC_{β} and size are **not correlated**, using $\beta = 1.1055$, and the parameters from model 1 in the previous section. Pearson correlation between the two variables is $r << 0.001$, and Spearman correlation is $R = -0.04$.

The parameter β has eluded measurement, because it can only be observed on sufficiently large collections of programs written in the same language and that, collectively and empirically, define what is to be expected of programs written in that language. We now have the means to measure it, as shown in this paper. Therefore, we now have the knowledge to create updated versions of well-known software metrics that are truly independent of size and that may (or may not) carry additional important information about the code that is not already captured by size metrics. If, for example, high coupling really is “bad”, we now have the mathematical knowledge to measure the size-independent essence of coupling. We plan to investigate the statistical power of this seemingly small, but critical, adjustment in future work.

8. Conclusion

We have described a quantitative study designed to answer the question: does the scale of a software system affect the internal structure of its modules? We have made an important step into answering this question by performing a statistical analysis of a very large and varied collection of Java

projects. The statistical significant results in this dataset are strong: there are, indeed, superlinear effects on some aspects of the modules' internal structure and composition with other modules. This reinforces the widely accepted idea that programming-in-the-large carries with it different concerns that aren't as strongly present for programming-in-the-small. More importantly, it has tremendous consequences for software metrics in general. Many of the metrics proposed in the literature, and that are used widely in IDEs, have suffered from poor information content for prediction models because they correlate with the much simpler size metrics. Our paper shows how this can be corrected.

Acknowledgments

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A. Additional Plots

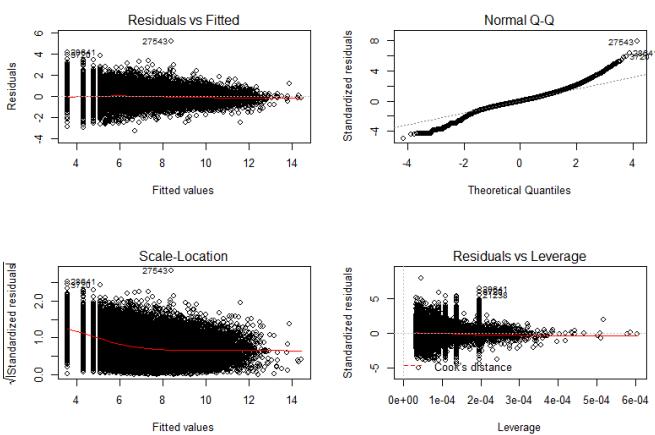


Figure 11. Residuals of SLOC ~ Modules.

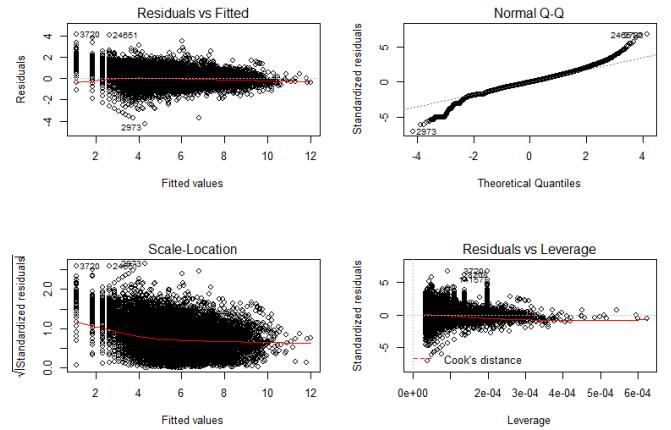


Figure 12. Residuals of Methods (in classes) ~ Classes.

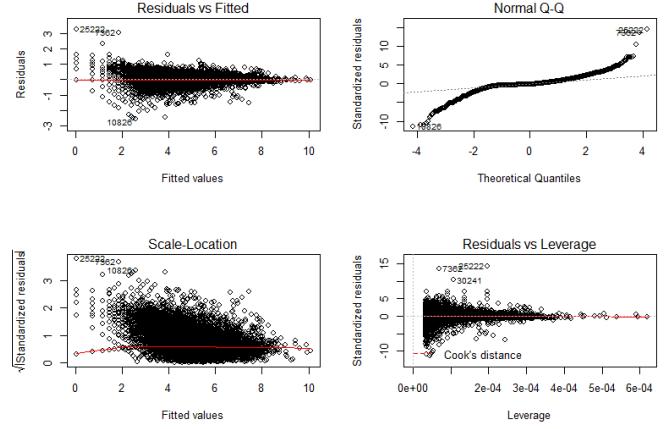


Figure 13. Residuals of Constructors ~ Classes.

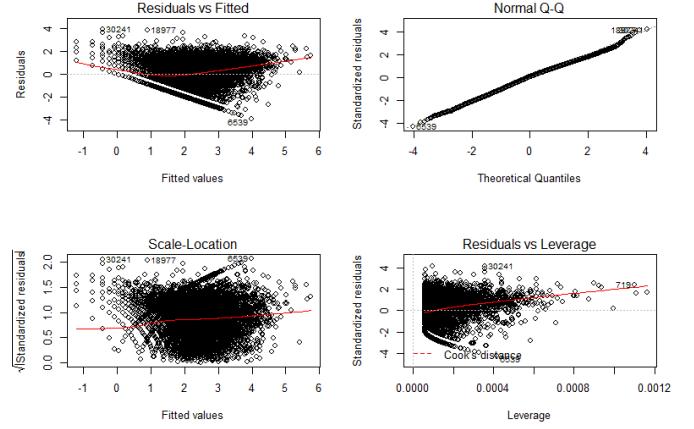


Figure 14. Residuals of Interfaces ~ Classes.

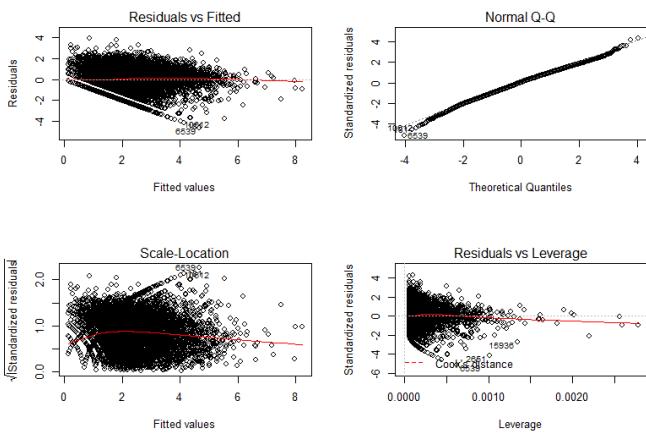


Figure 15. Residuals of Interfaces \sim Classes. Classes in \log^2 scale.

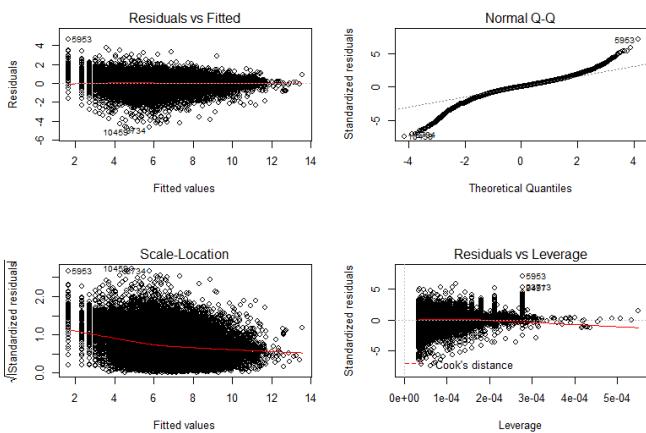


Figure 16. Residuals of Calls \sim Methods.

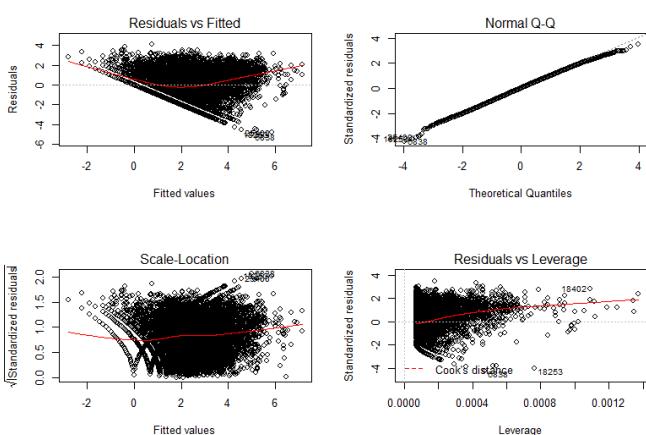


Figure 17. Residuals of Instanceof statements ~ Methods.

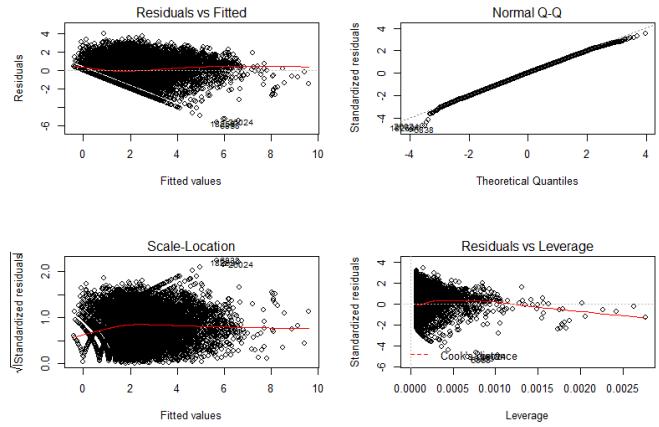


Figure 18. Residuals of Instanceof statements \sim Methods. Methods in \log^2 scale.

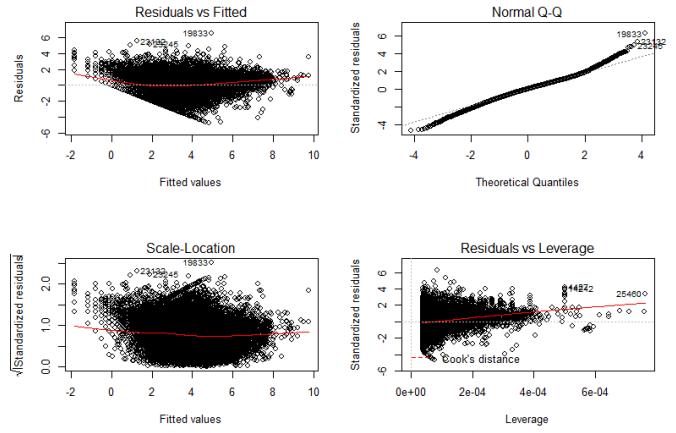


Figure 19. Residuals of Casts ~ Methods.

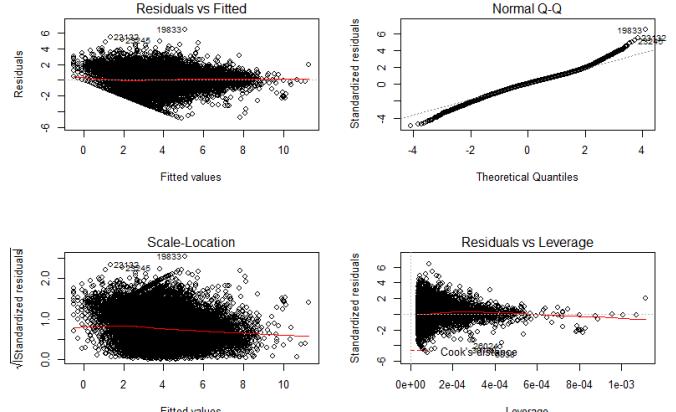


Figure 20. Residuals of Casts \sim Methods. Methods in $\log^{1.4}$ scale.

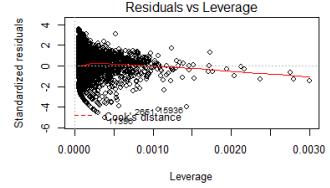
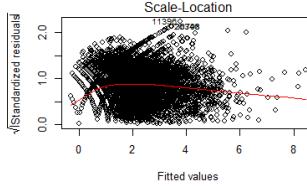
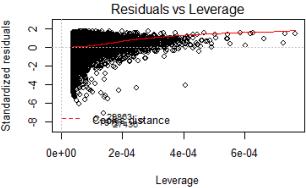
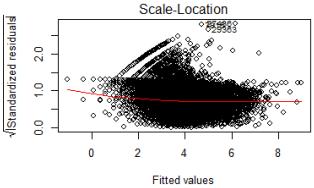
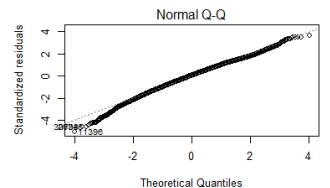
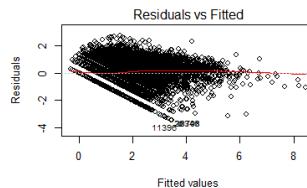
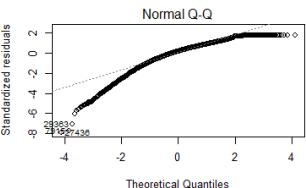
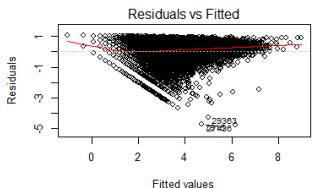


Figure 21. Residuals of classes defined using inheritance (DUI) \sim Classes.

Figure 24. Residuals of classes inherited from (IF) \sim Classes. Classes in \log^2 scale.

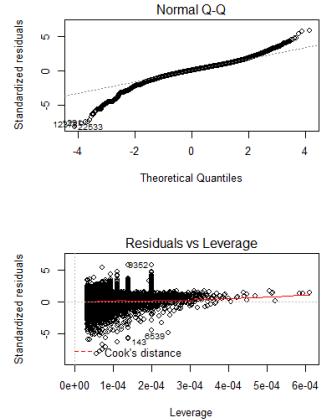
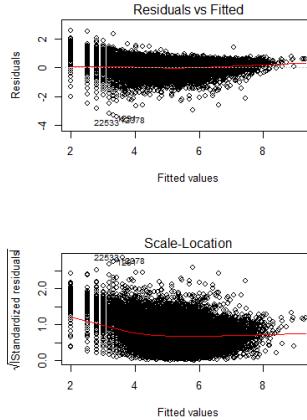
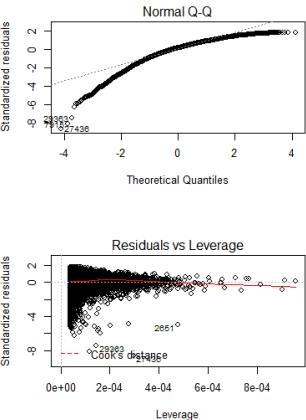
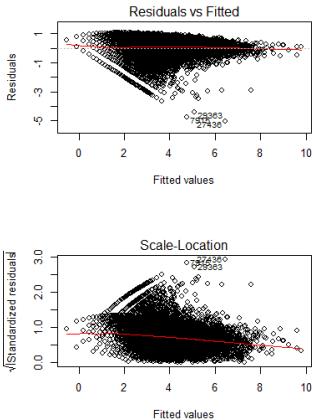


Figure 22. Residuals of classes defined using inheritance (DUI) \sim Classes. Classes in $\log^{1.2}$ scale.

Figure 25. Residuals of used modules \sim Declared modules. Classes in \log^2 scale.

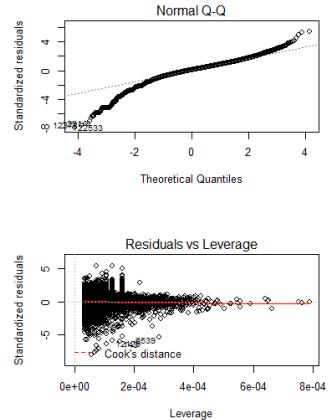
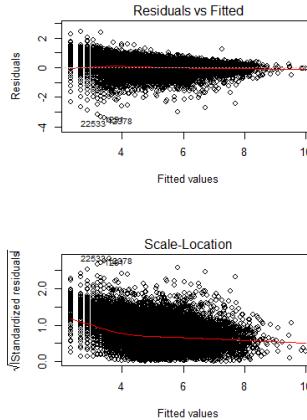
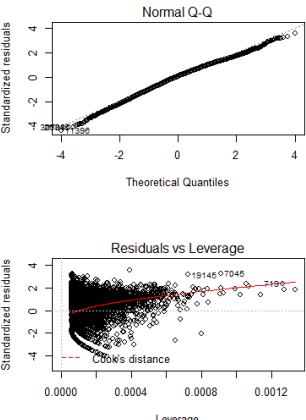
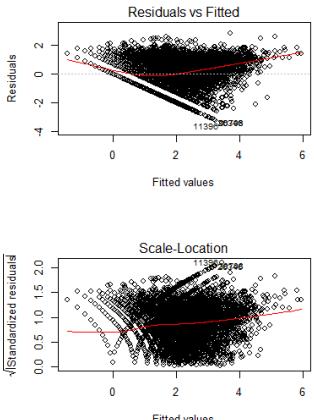


Figure 23. Residuals of classes inherited from (IF) \sim Classes.

Figure 26. Residuals of used modules \sim Declared modules. Classes in \log^2 scale.

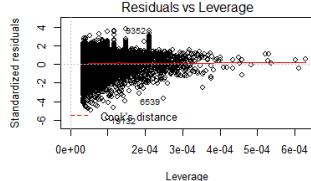
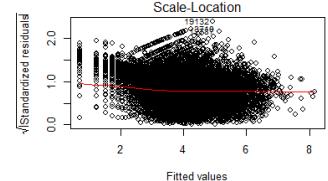
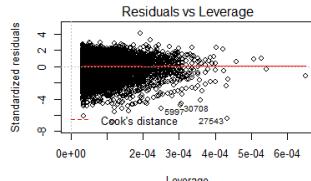
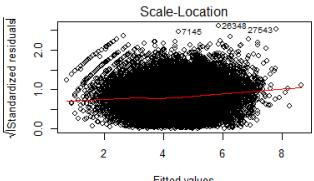
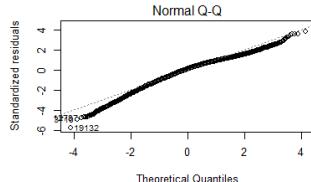
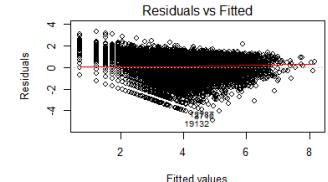
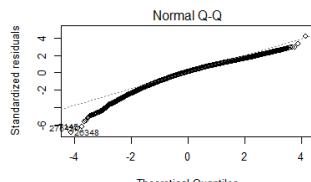
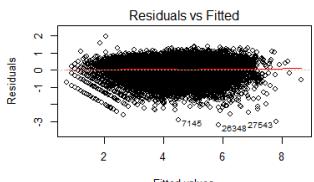


Figure 27. Residuals of efferent coupling \sim SLOC.

Figure 30. Residuals of used external modules \sim Declared modules.

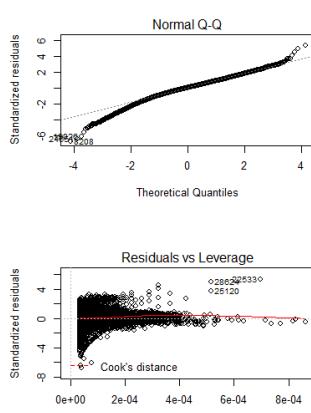
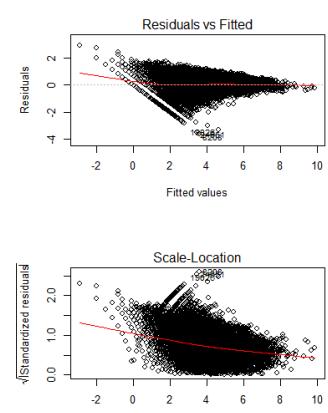
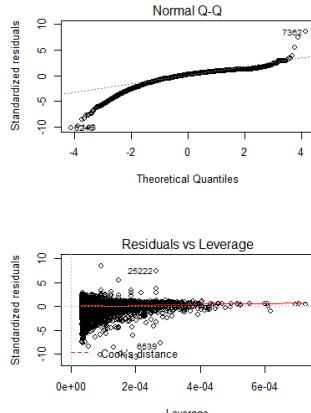
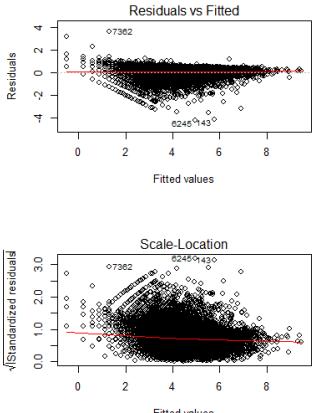


Figure 28. Residuals of used internal modules \sim Declared modules.

Figure 31. Residuals of used internal modules \sim Total used modules.

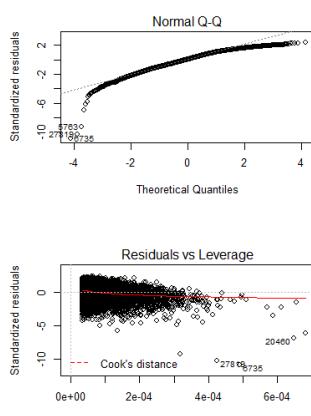
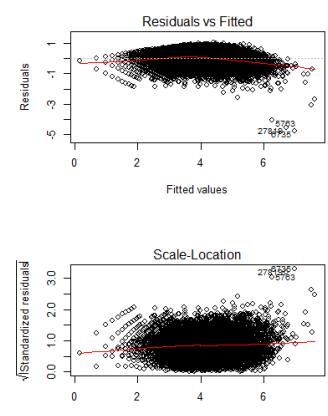
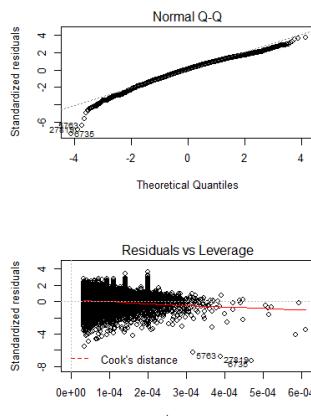
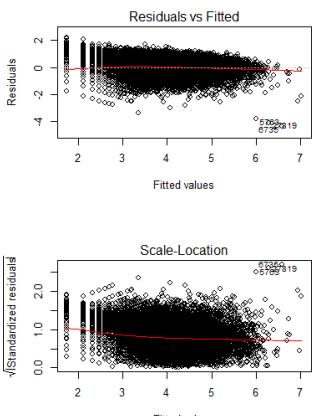


Figure 29. Residuals of used JDK modules \sim Declared modules.

Figure 32. Residuals of used JDK modules \sim Total used modules.

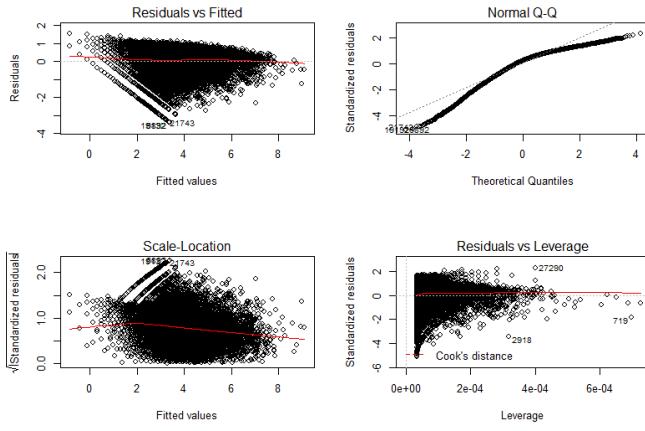


Figure 33. Residuals of used external modules \sim Total used modules.

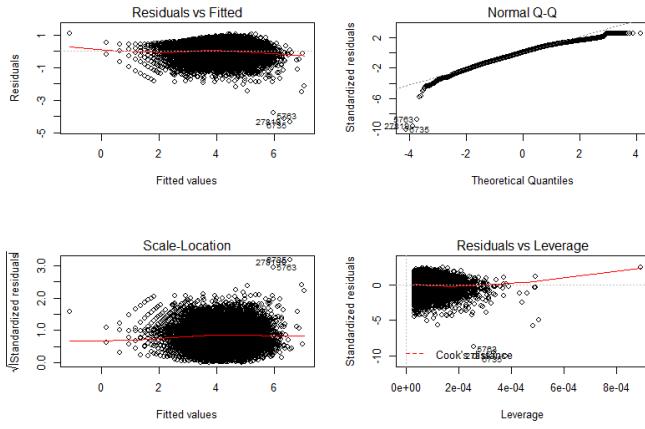


Figure 34. Residuals of used internal modules \sim Total used modules. RLM.

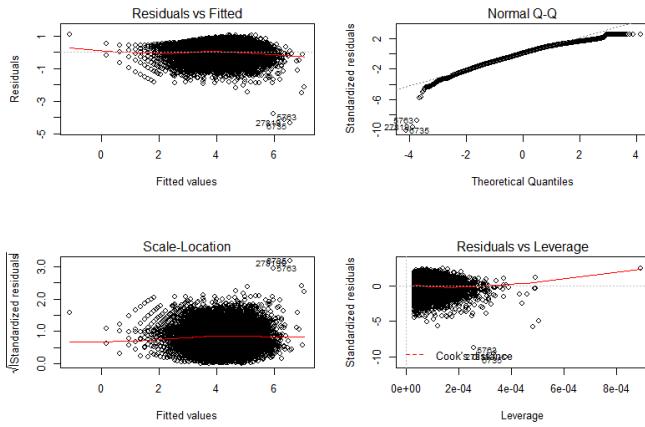


Figure 35. Residuals of used JDK modules \sim Total used modules. RLM.

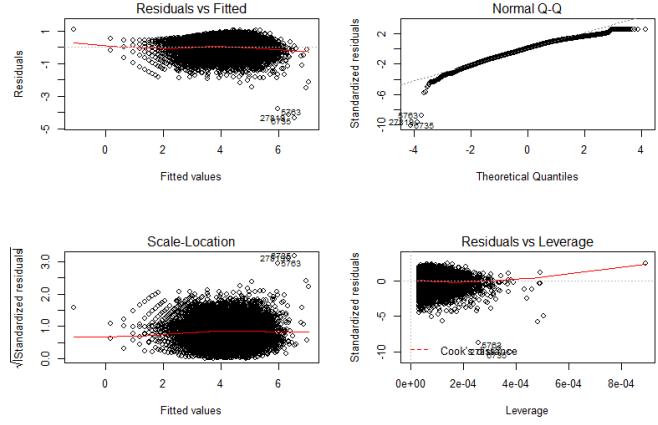


Figure 36. Residuals of used external modules \sim Total used modules. RLM.

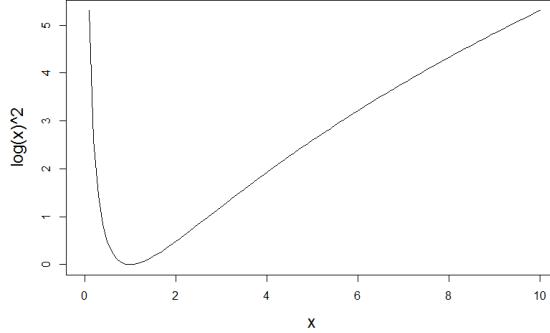


Figure 37. Generic $\log(x)^2$ function.

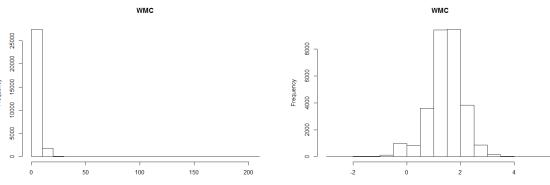


Figure 38. Histogram of WMC. Left: Linear scale. Right: Log scale.